Introduction to Particle Physics

Laurence Littenberg

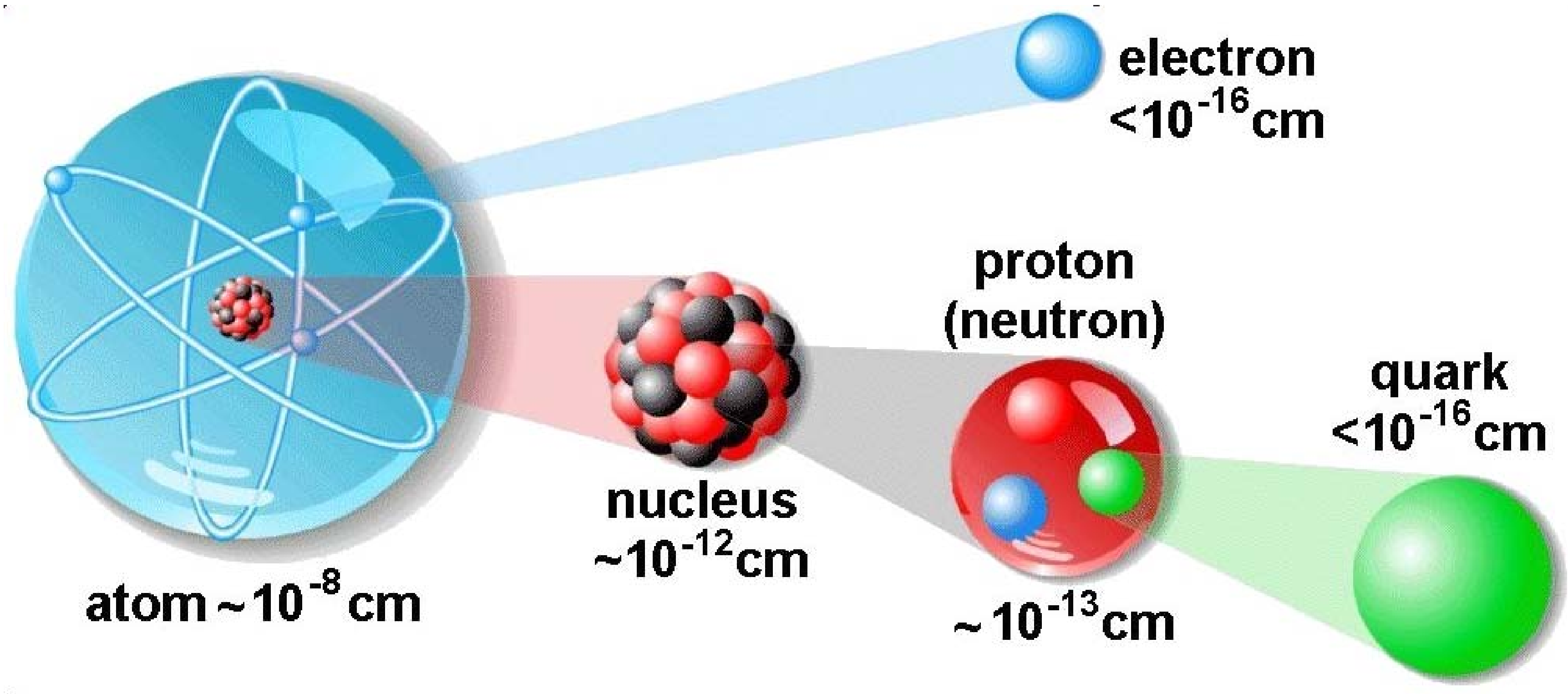
1. The Object
2. Some History & Background
3. The Standard Model
4. The Tools
5. Open Issues

See also http://particleadventure.org/particleadventure/

A history of intellectual upheavals

- Quantum mechanics
  - No more clockwork universe; can't predict things exactly
  - Particles can interfere like waves
  - Existence of intrinsic angular momentum (tops that won't quit)
- Substructure to protons & neutrons that can never escape!
- Existence of particles that can penetrate miles of lead (ν's)
- Existence of anti-particles
- Existence of particles no one seems to need (muons, etc.)
- Violation of intuitively compelling symmetries
  - Mirror symmetry (parity), time-reversal invariance
  - Charge-parity invariance, CP-invariance
- Two forces 1000 times different in strength are really the same
- A "pointlike" particle as heavy as a gold nucleus (it has to be more than 30,000,000,000,000 times denser than a neutron star)
- The world has more than 3 spatial dimensions (maybe 10)

Search for the most fundamental building blocks of matter



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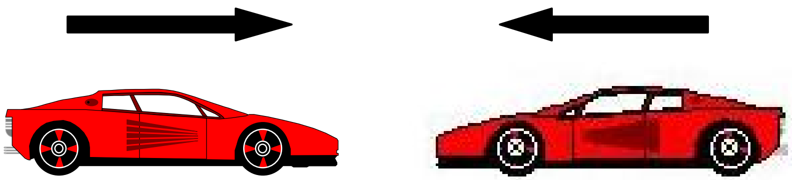
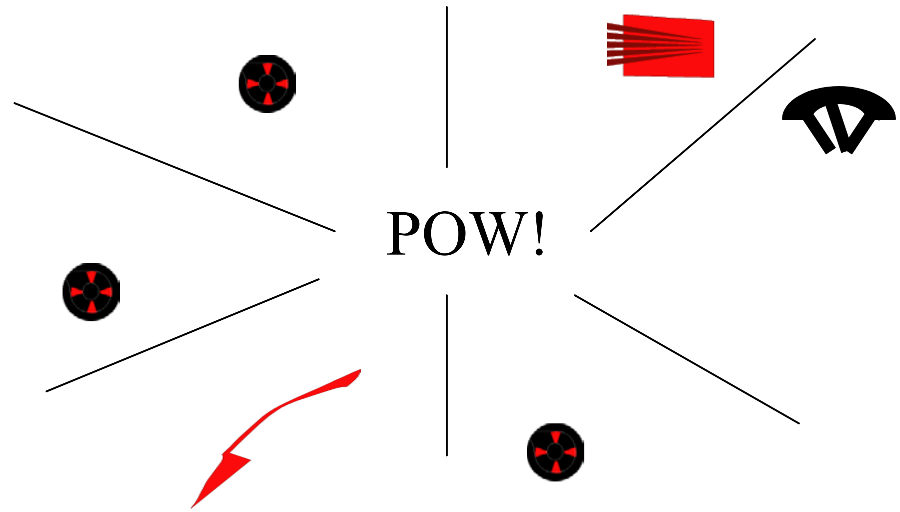
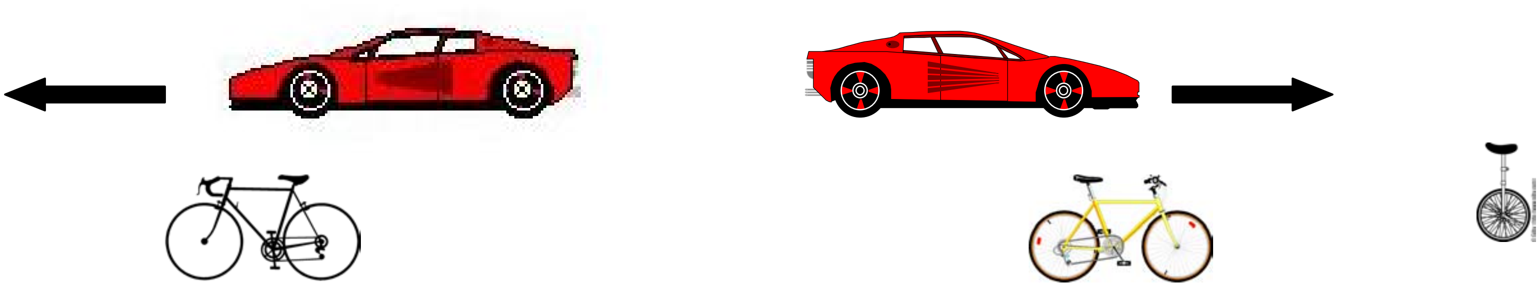


What are cars made of?



OK for nuclei
But for nucleons…



Why? E=mc^2 and quarks

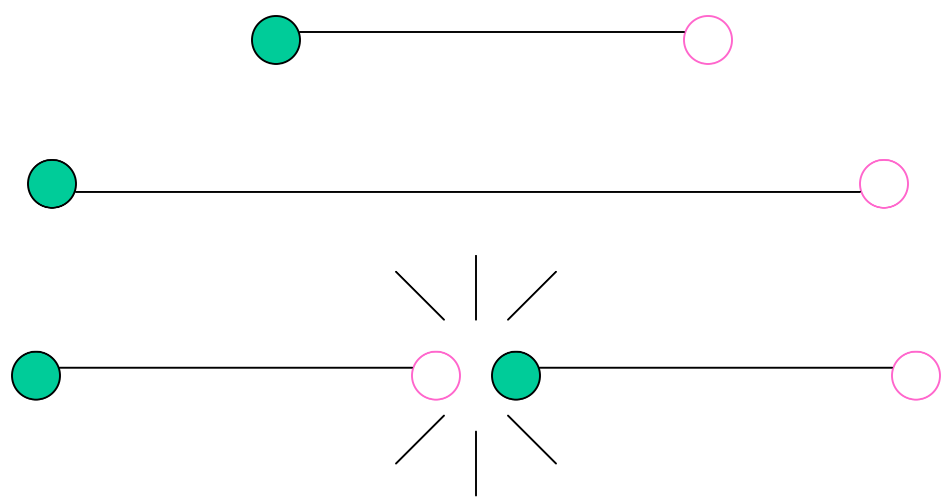
Free quarks?

Many searches – Stanford, Australia, etc.

Confinement – **never** see a free quark

$$V(r) = q_1 q_2/r + \alpha r$$

i.e. like a rubber band-energy grows as quarks pull apart:



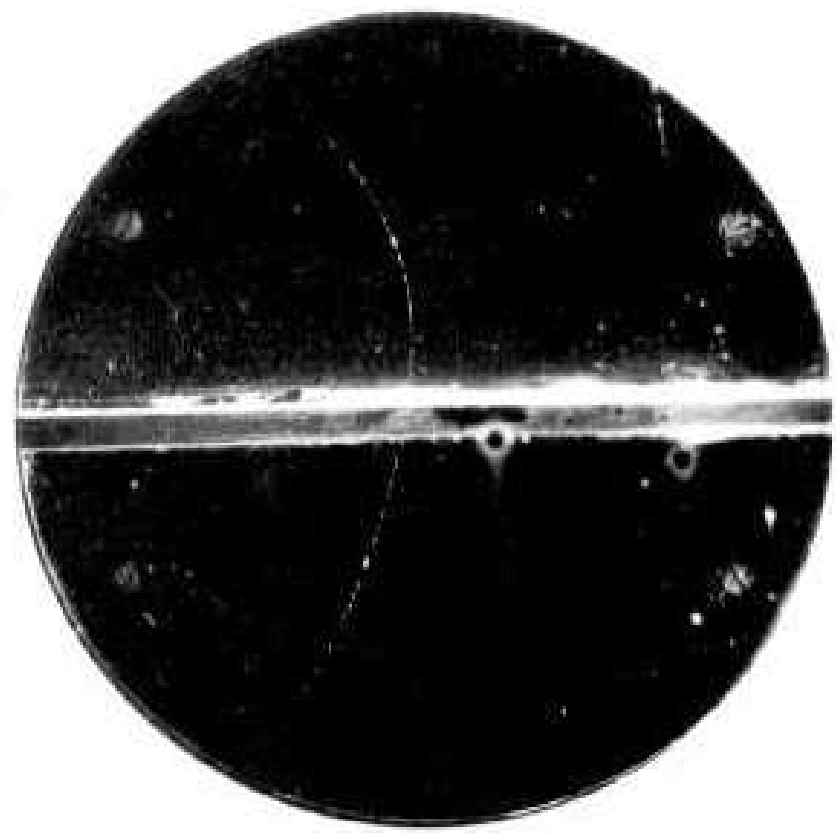
The First Generation of Fermions

Contains the constituents of all everyday ordinary matter, u & d quarks and electrons plus the neutrino 'invented' by Pauli (1928), named by Fermi (1933). First directly observed by Reines & Cowan (1956).

	quarks		leptons
$+\frac{2}{3}e$	u	0	ν
$-\frac{1}{3}e$	d	-e	e

Antimatter

In 1928 P.A.M. Dirac predicted the electron would have a partner with all the same properties (mass, spin), except that the electric charge would be positive. Five years later, Carl Anderson observed an electron with the "wrong" sign. The track to the right is headed up:



In general every particle has an anti-particle. "Discrete" properties such as electric charge, lepton & baryon "number", charm, strangeness, etc. are all reversed. ***Some*** neutral particles are their own antiparticles. Charged particle-antiparticle pairs can annihilate into photons or other lighter particles.

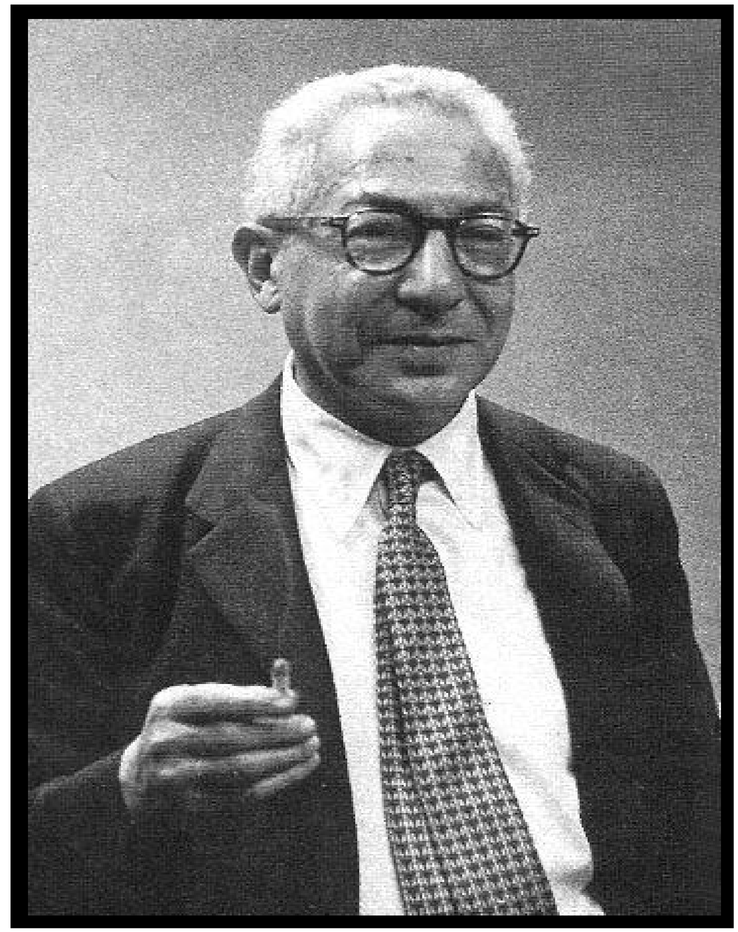
The muon

Discovered in cosmic rays by Neddermeyer and Anderson (1936)

Appears identical to electron but 200 times as heavy

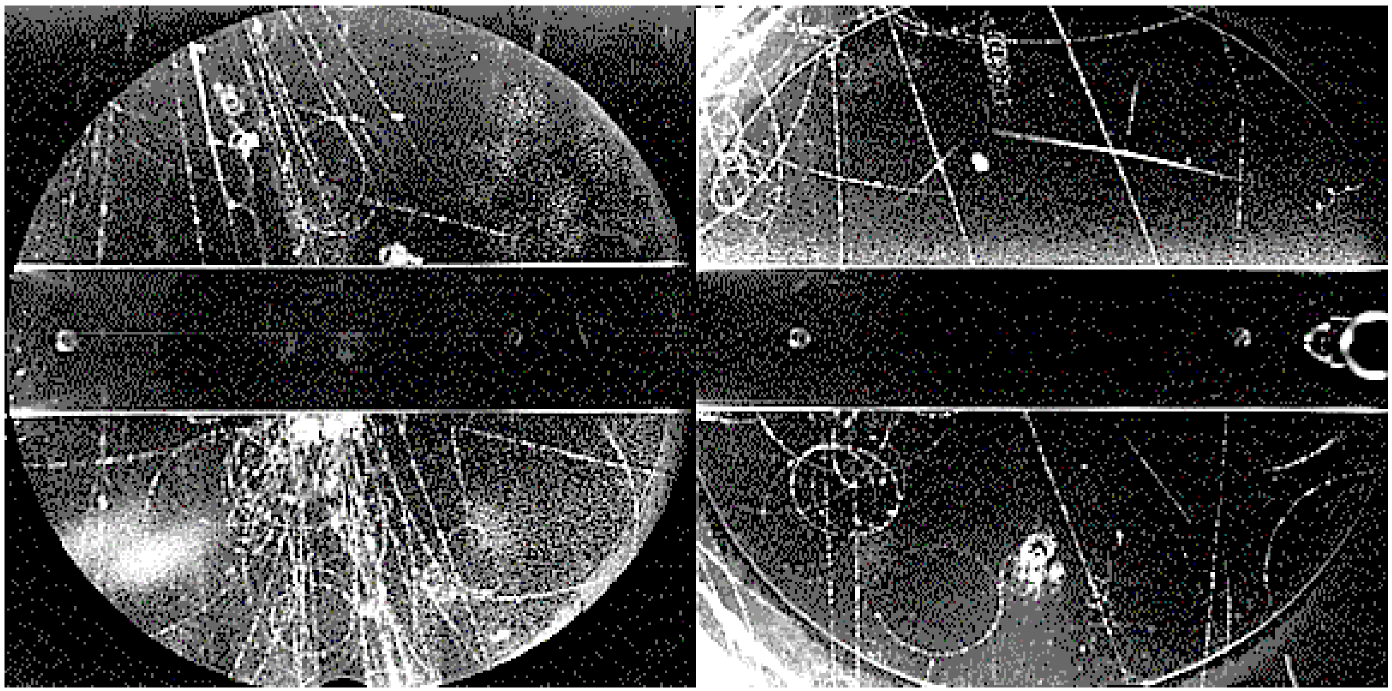
Decays within 2.2 μsec

‘Who ordered that?’ - I I Rabi



Strange Particles

In 1947 Rochester and Butler discovered a new class of objects, now known to contain a third quark



First observations of a neutral (left) and a charged (right) kaon in a cloud chamber

By the early 1960s beautiful patterns of particles containing three quarks or a quark and an antiquark were seen which were predictive

Particles with Half-integer Spins

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Hadrons

"Color" is analogue of electric charge for strong force (QCD not QED) instead of two possibilities (+,-), there are six (red, green, blue, and their anti-colors). Colored objects can't exist isolated in the normal world. Can have say red+anti-red (mesons), but also red+ green+ blue (baryons).

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Forces between elementary particles at ~ 1 GeV

• Strong	~ 1
• Electromagnetic	~1/137
• Weak	$\sim 10^{-5}$
• Gravity	$\sim 10^{-39}$

Examples:

Standard Model treats E-M, weak in unified way.
At high energy these have equal strength

Carriers of Force

Force	**"Transmitter"**	**Range**†
Strong	Gluons,Mesons	$\sim 10^{-13}$ cm
Electromagnetic	Photons	∞
Weak	W,Z	$\sim 3 \times 10^{-16}$ cm
Gravity	Gravitons(?)	∞

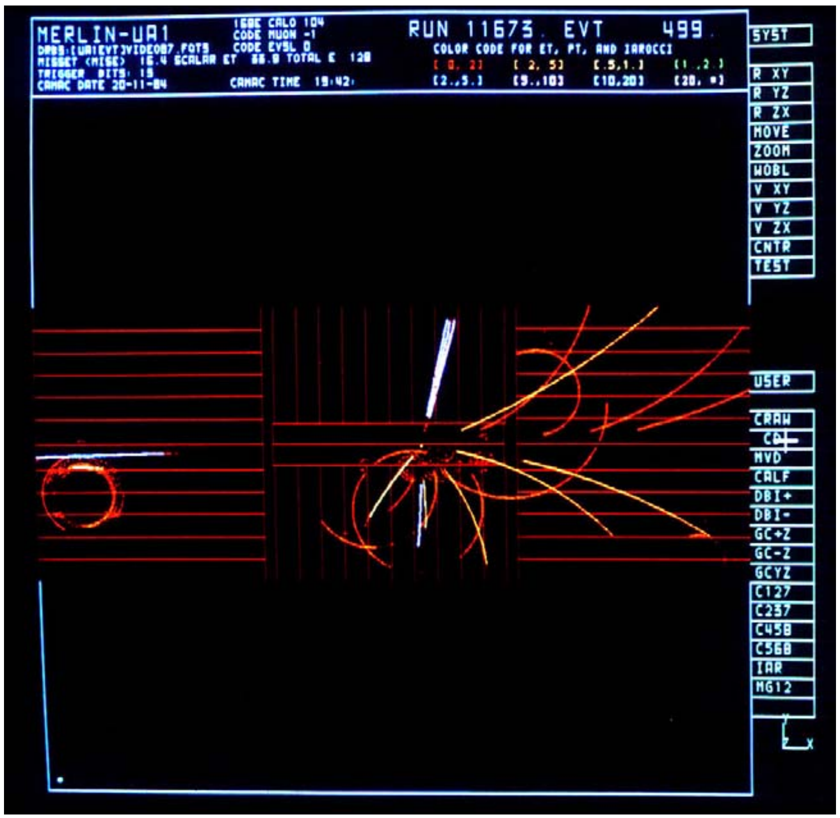
$$^{\dagger}\, R \sim \frac{hc}{2\pi\, mc^2} = \frac{0.2 GeV}{mc^2} \times 10^{-13}\, cm$$

W, Z "particles"

Carriers of the weak force
1984 CERN Rubbia, van der Meer

$$p+\overline{p}\rightarrow W^{\pm}+X;\quad W^{\pm}\rightarrow e^{\pm}\upsilon,\, \mu^{\pm}\upsilon\ or\ \tau^{\pm}\upsilon;\quad M_{W}=80.4\,GeV$$

$$p+\overline{p}\rightarrow Z^{0}+X;\quad Z^{0}\rightarrow e^{+}e^{-},\, \mu^{+}\mu^{-}\ or\ \tau^{+}\tau^{-};\quad M_{Z}=91.2\,GeV$$



Decay of a W into τν in UA1. The decay of the τ, probably into 3 charged pions, can be seen as an isolated "pencil" jet at the top center

Particles with Integer Spin

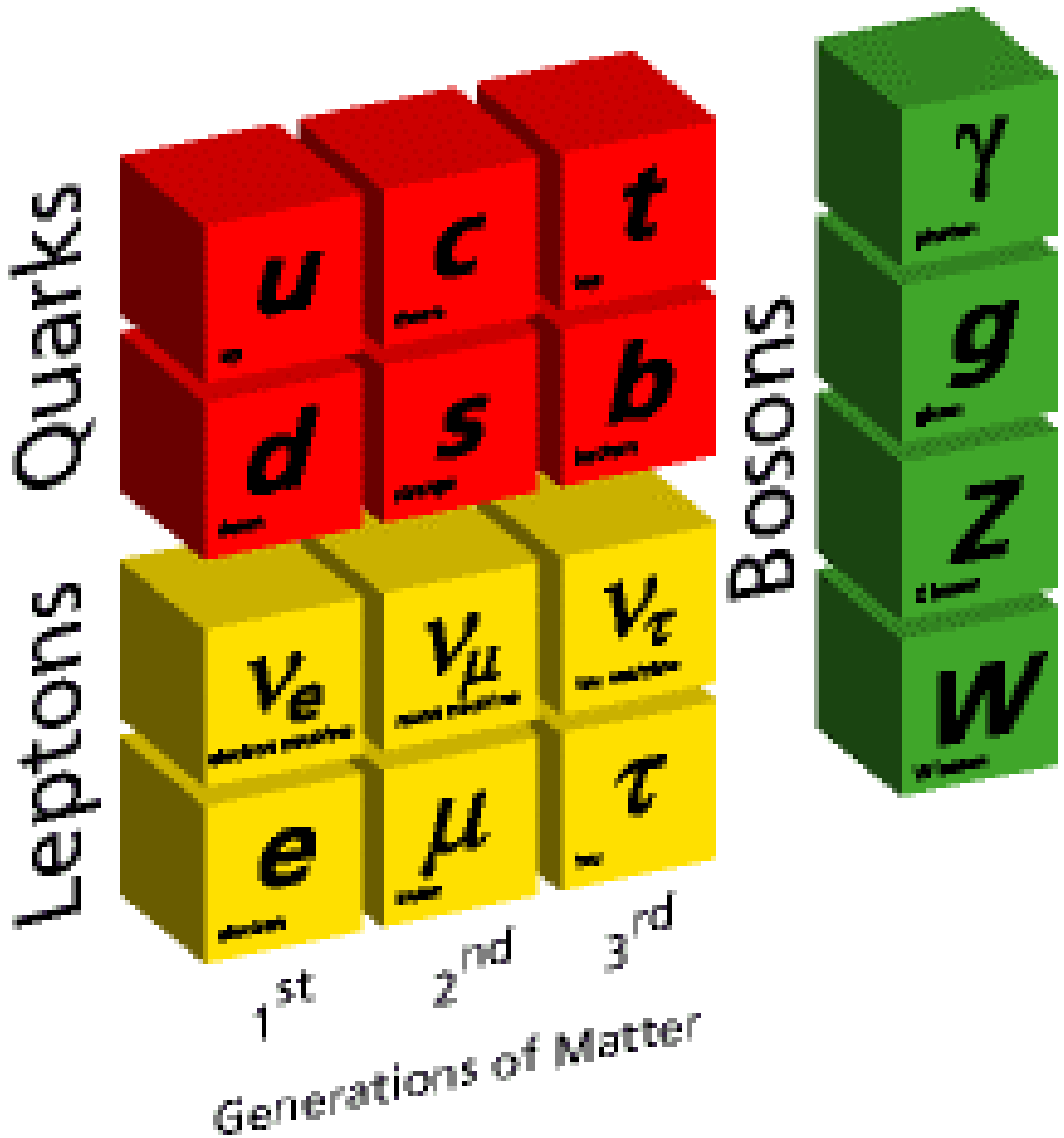
BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Gravity spin = 2		
G	0	0

Elementary Particles



Conservation Laws

Some quantities can't be increased or decreased through interactions. Most people have heard of the conservation of energy, for example. Another absolutely conserved quantity is electric charge. If you start out with a system containing no charges, you may end up with lots of charges but there have to be as many positive ones as negative.

0 => + - => ++-- => +++--- => etc.

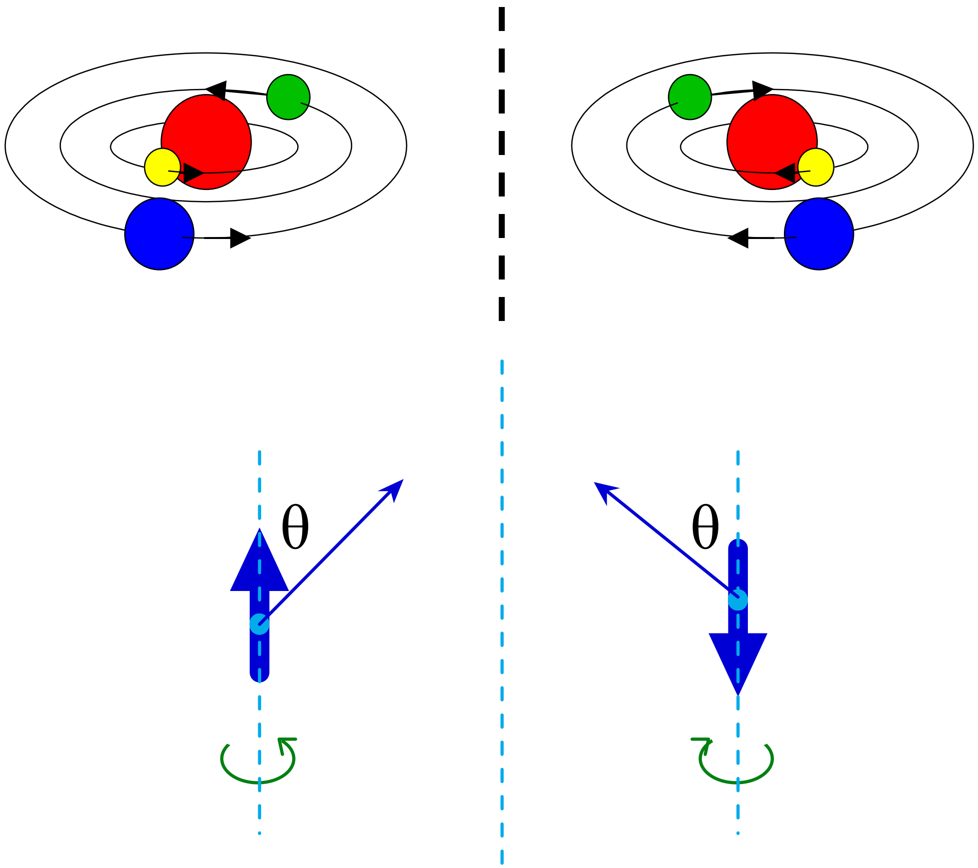
The are a number of other charge-like quantities in physics, for example, baryon number (B). Some are conserved by one kind of force but not by others. An example is strangeness (S) which is conserved by the strong force but not by the weak force. Such "partially conserved" quantities have analogues in our every day life. One is money ($) , for example. Can you think of any others?

There are other conservation laws called invariance principles. These include parity (P), time reversal (T), charge conjugation (C) , etc.

Conserved Quantities

Quantity	Strong	E-M	Weak	Tested
Energy	Yes	Yes	Yes	
Momentum	Yes	Yes	Yes	
Angular Momentum	Yes	Yes	Yes	✓
Charge	Yes	Yes	Yes	
Lepton number	Yes	Yes	Yes	✓
Lepton type	Yes	Yes	Not always	✓
Baryon	Yes	Yes	Yes	✓
CPT	Yes	Yes	Yes	✓
Parity	Yes	Yes	No	
Strangeness	Yes	Yes	No	
Time reversal	Yes	Yes	No	
Charge conjugation	Yes	Yes	No	
CP	Yes	Yes	A little	✓

Parity violation



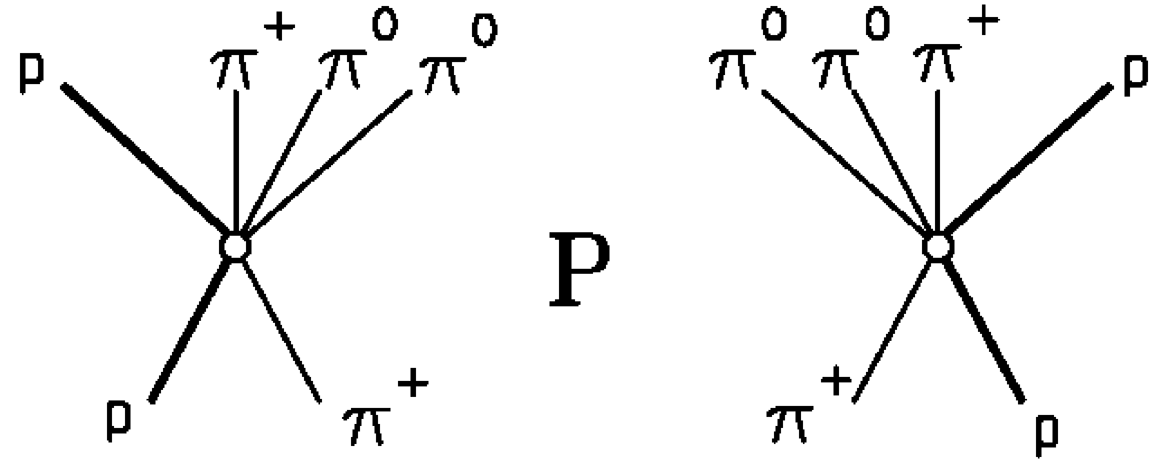
Macroscopic systems obey the same physical laws in a mirror system, e.g. planetary motion "parity conservation".

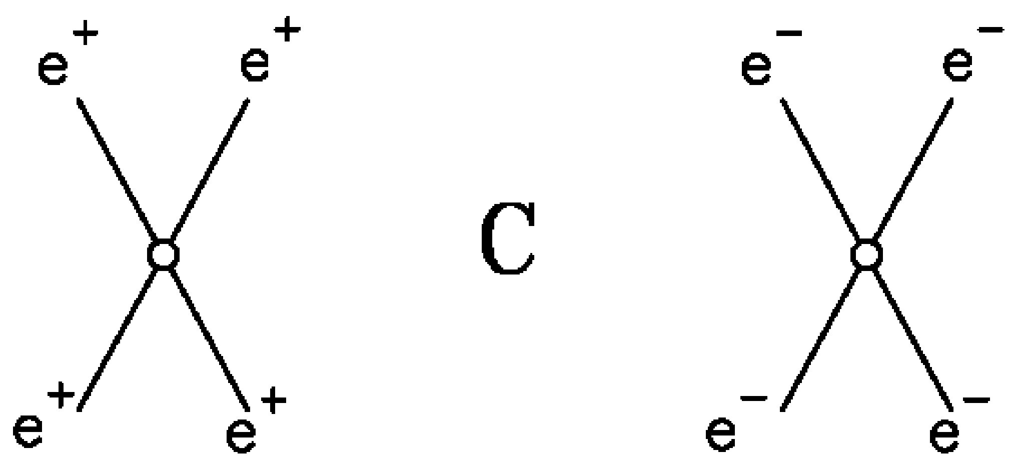
β-decay (weak interaction) does not conserve parity.

Discovered in 1956 in polarized ^{60}Co decay.

$$I(\theta) = 1 - \frac{v}{c}\cos\theta$$

P and C reversal

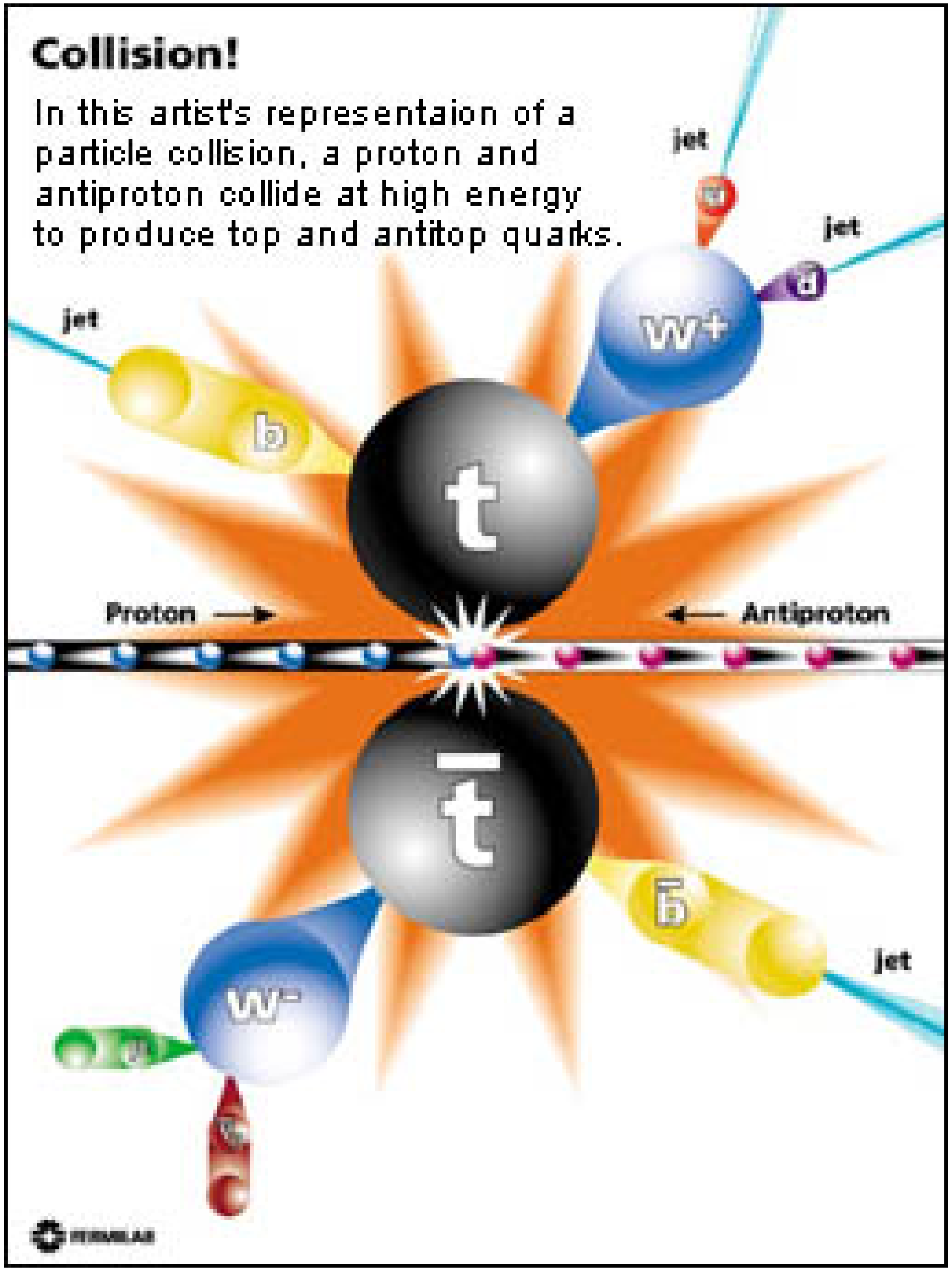




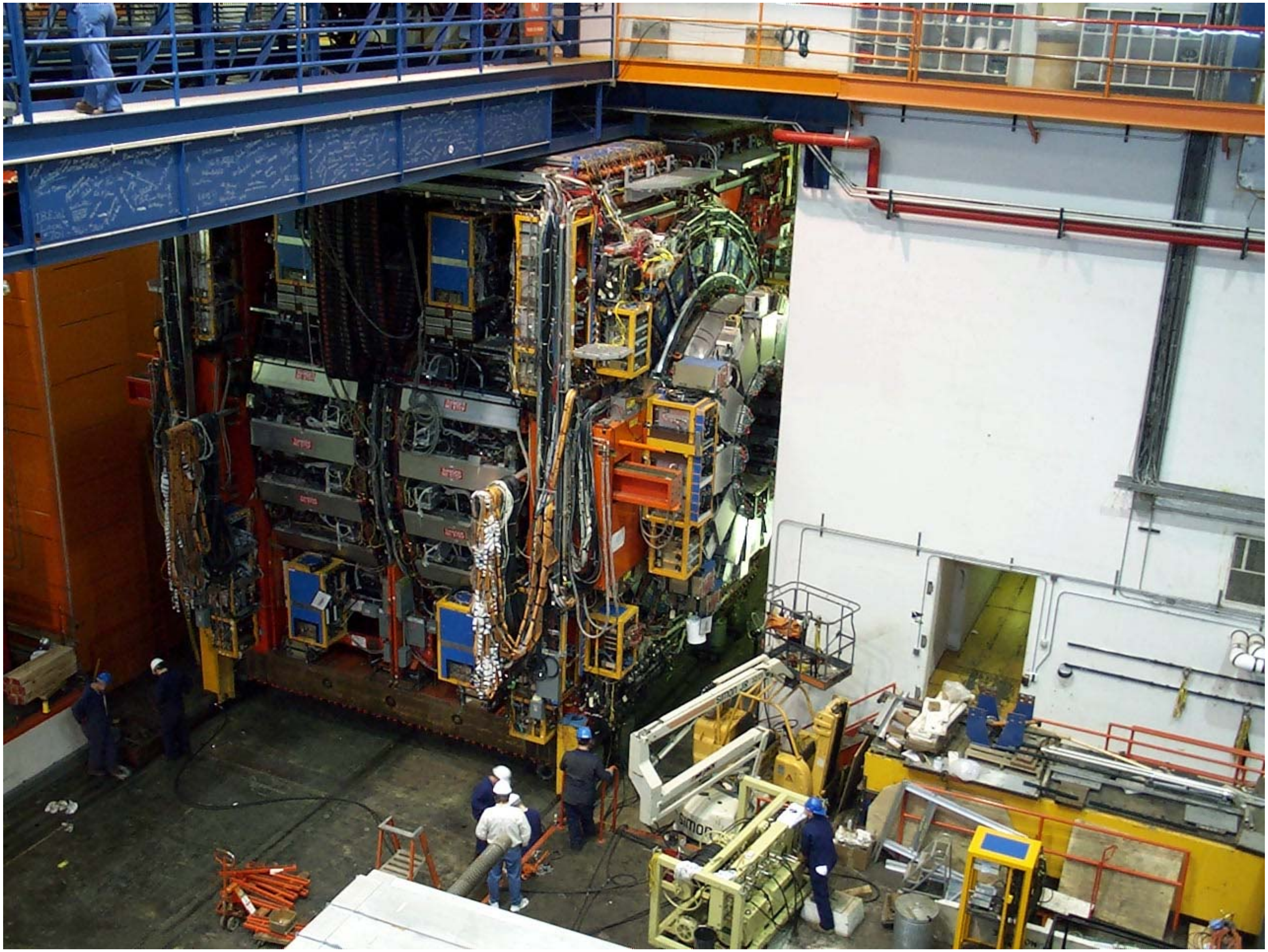
Accelerators

Accelerator	**Location**	**Beam 1**	**Beam2**	**Comment**
AGS	Brookhaven	30 GeV p	Fixed tgt	2ndary beams
TeVatron	FNAL (Illinois)	900 GeV p	900 GeV pbar	
LHC	CERN (Geneva)	7 TeV p	7 TeV p	2007
HERA	DESY (Hamburg)	920 GeV p	30 GeV $e^{\pm}$	
LEP	CERN	100 GeV e^-	100 GeV e^+	now closed
CESR	Cornell	5 GeV e^-	5 GeV e^+	Ψ resonance
KEK-B	Tsukuba, Japan	8 GeV e^-	3.5 GeV e^+	Ψ asymmetric
PEP-II	SLAC (Stanford)	9 GeV e^-	3.1 GeV e^+	Ψ asymmetric
DAΦNE	Frascati (Italy)	0.51 GeV e^-	0.51 GeV e^+	Φ resonance

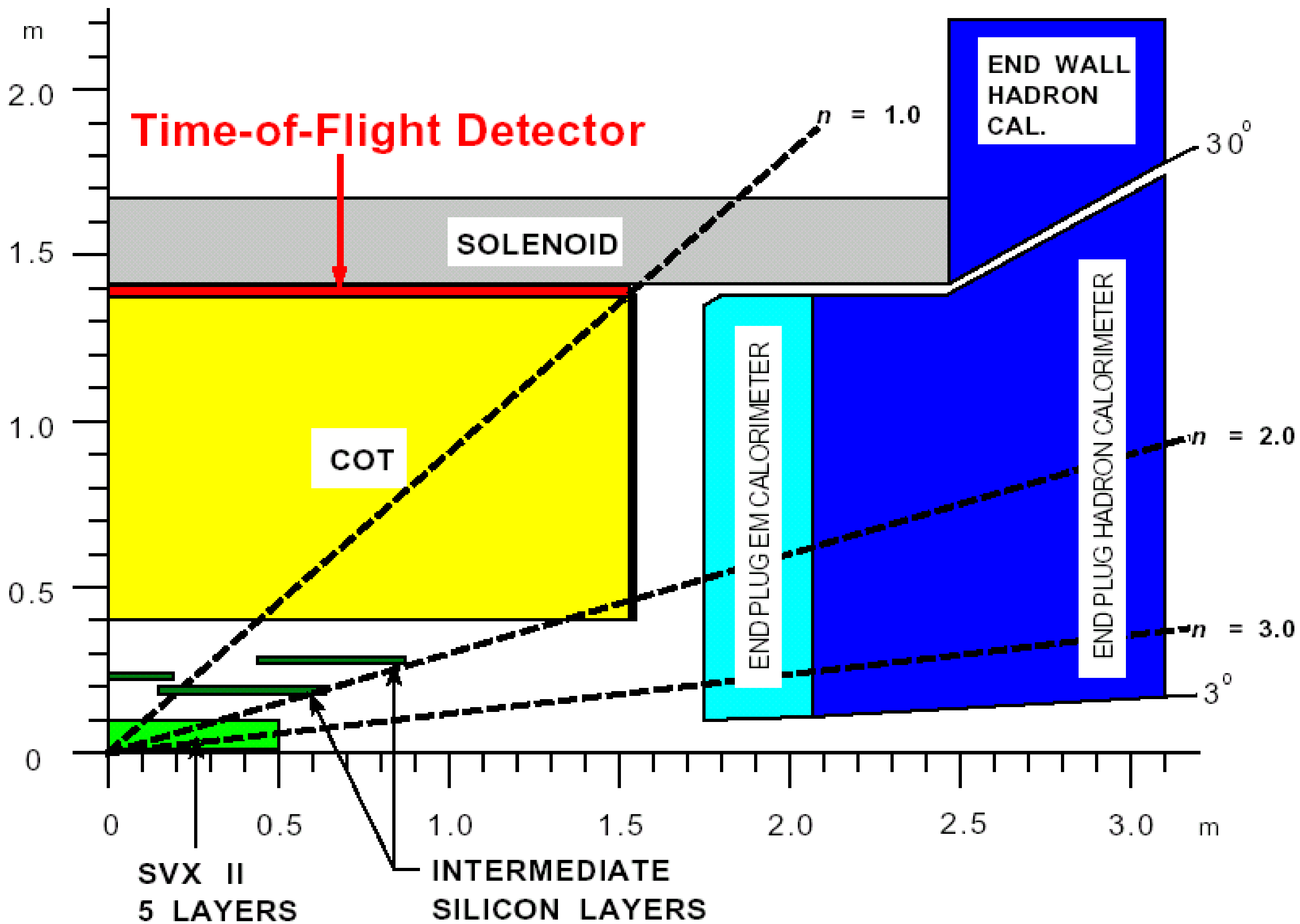
Production of top quark



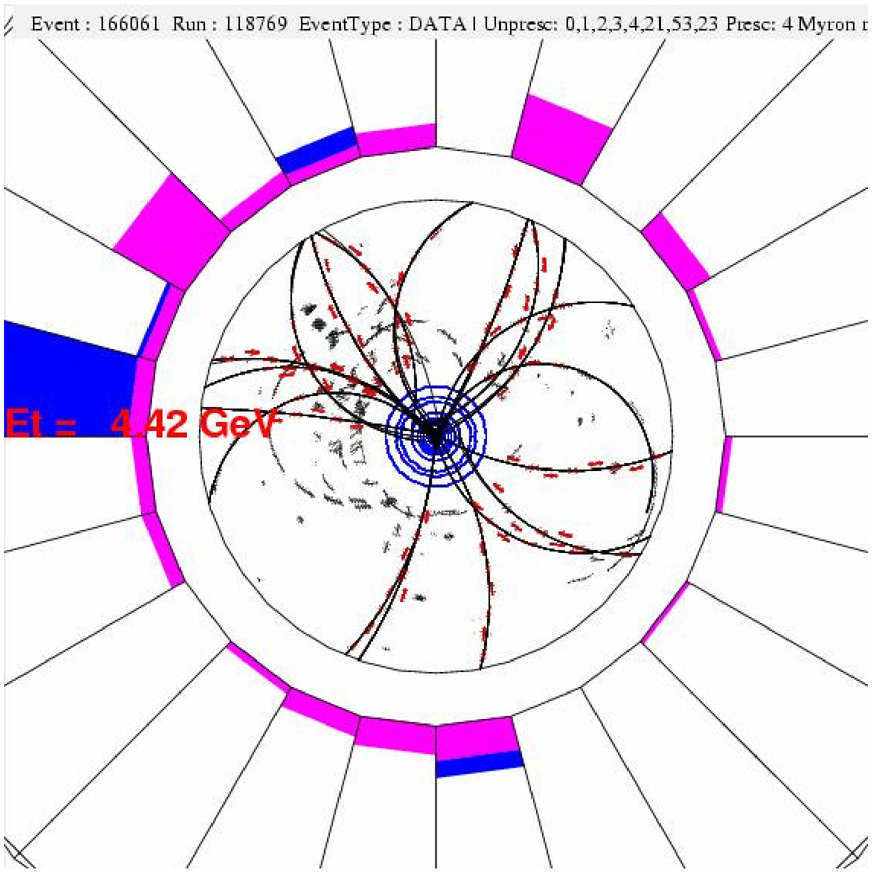
CDF Detector at Fermilab

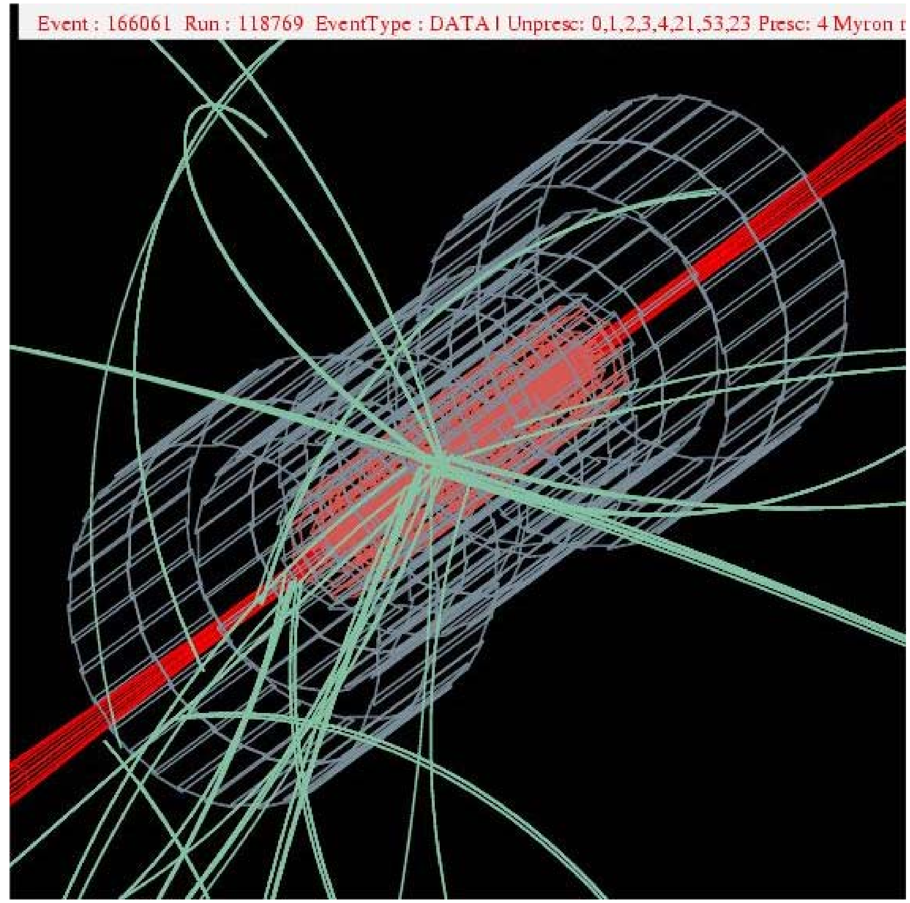


Schematic of Inner CDF Detector



What Physicists actually “see”





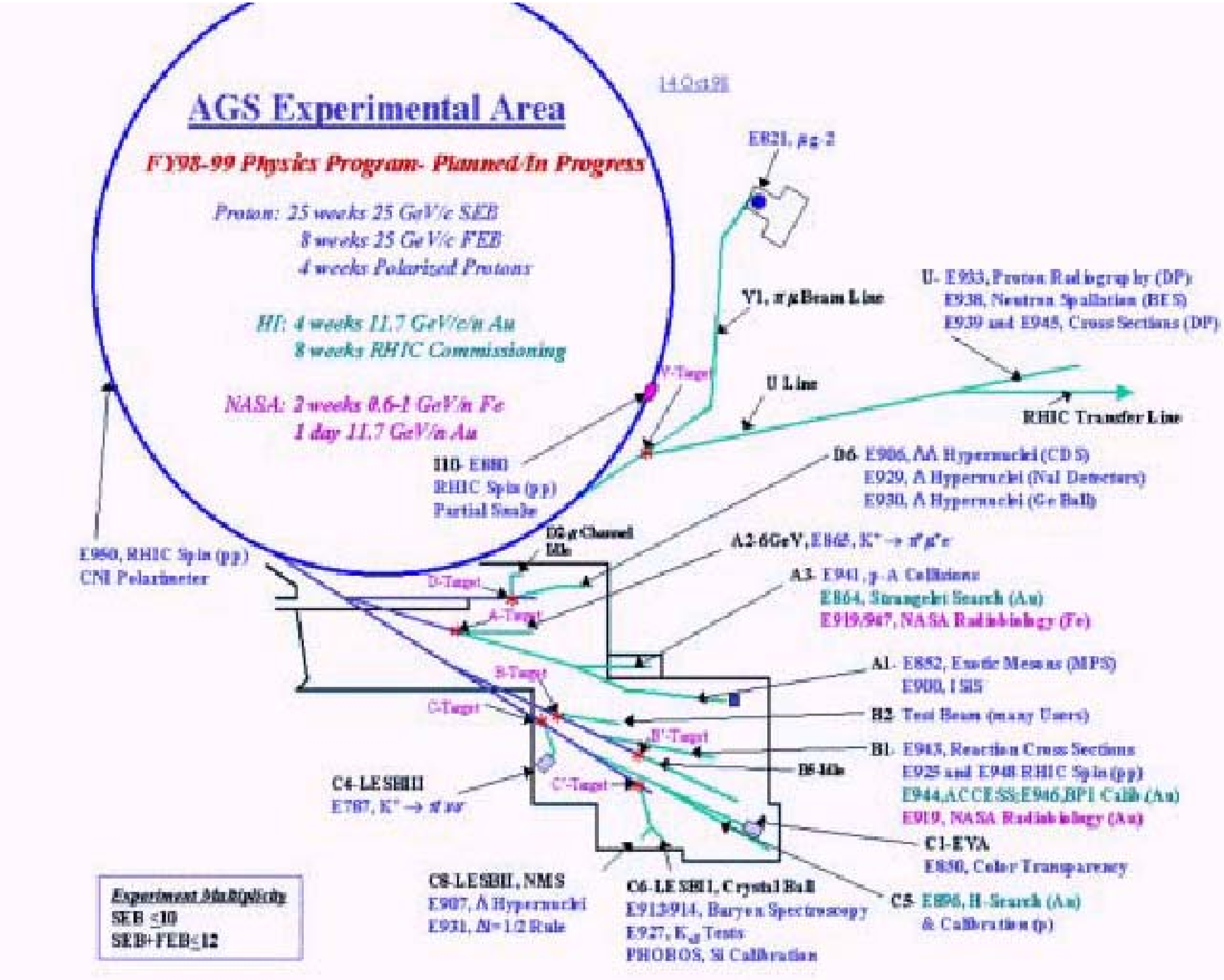
End view

3d reconstruction

(CDF event)

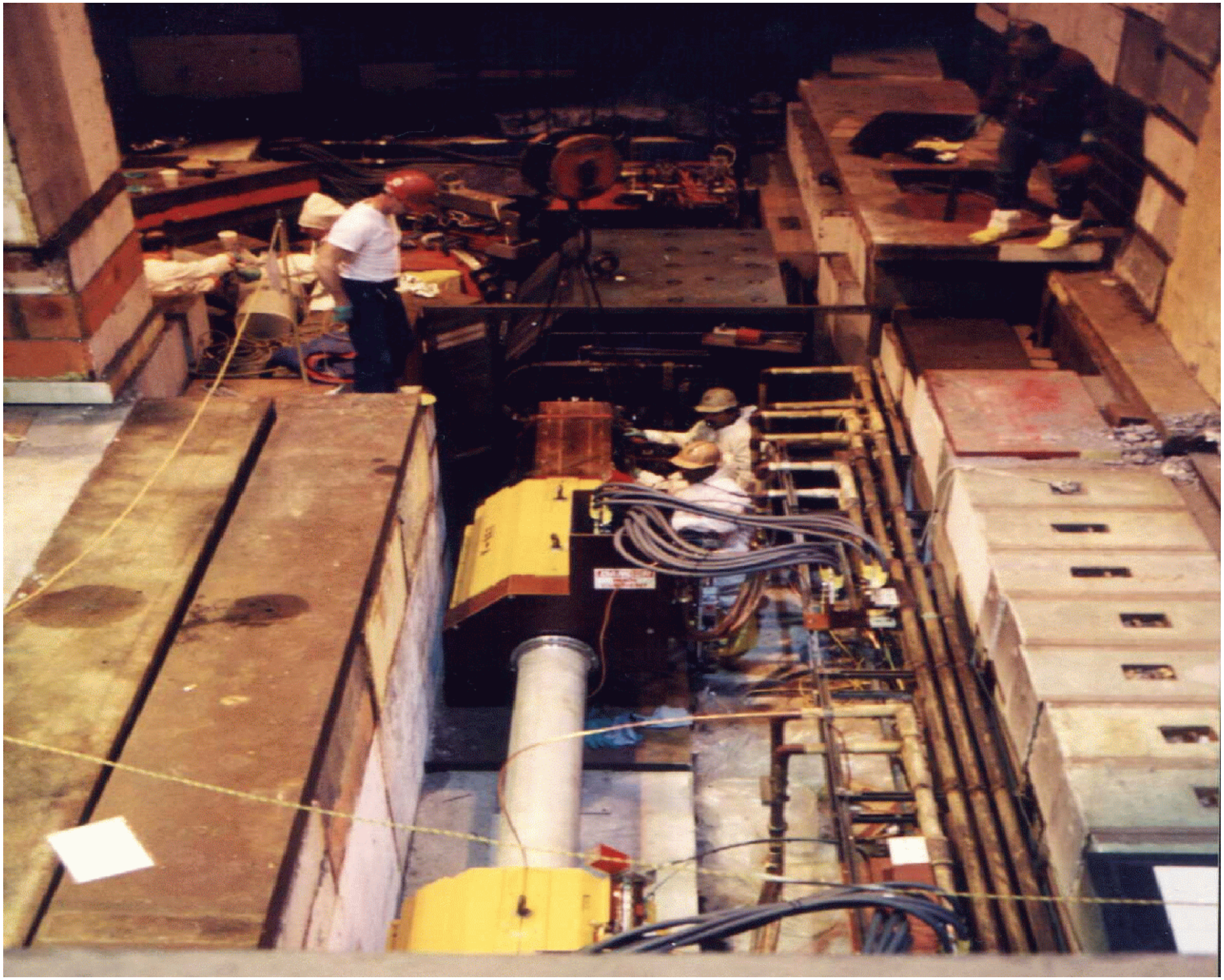
AGS Complex at BNL

Inside the AGS



AGS Experimental Area
FY98-99 Physics Program- Planned/In Progress
Proton: 25 weeks 25 GeV/c SEB
8 weeks 25 GeV/c FEB
4 weeks Polarized Protons
HI: 4 weeks 11.7 GeV/c/n Au
8 weeks RHIC Commissioning
NASA: 2 weeks 0.6-1 GeV/n Fe
1 day 11.7 GeV/n Au
E821, μg-2
Y1, π/μ Beam Line
U- E933, Proton Radiography (DP)
E938, Neutron Spallation (BES)
E939 and E945, Cross Sections (DP)
U Line
RHIC Transfer Line
D6- E906, ΛΛ Hypernuclei (CDS)
E929, Λ Hypernuclei (NaI Detectors)
E930, Λ Hypernuclei (Ge Ball)
A2-6GeV, E865, K⁺ → π⁺μ⁺e
A3- E941, p-A Collisions
E864, Strangelet Search (Au)
E919/967, NASA Radiobiology (Fe)
A1- E852, Exotic Mesons (MPS)
E900, ISIS
B2- Test Beam (many Users)
B1- E943, Reaction Cross Sections
E925 and E940 RHIC Spin (pp)
E944,ACCESS;E946,BPI Calib (Au)
E919, NASA Radiobiology (Au)
C1-EVA
E850, Color Transparency
C5- E896, H-Search (Au)
& Calibration (p)
C6-LESB I, Crystal Ball
E912/914, Baryon Spectroscopy
E927, K_{el} Tests
PHOBOS, Si Calibration
C8-LESBII, NMS
E907, Λ Hypernuclei
E931, ΔI= 1/2 Rule
C4-LESBII
E787, K⁺ → π⁺νν̄
H10- E880
RHIC Spin (pp)
Partial Snake
E950, RHIC Spin (pp)
CNI Polarimeter
D-Target
A-Target
B-Target
C-Target
B'-Target
C'-Target
Experiment Multiplicity
SEB ≤10
SEB+FEB≤12

AGS Beamline Quadrupole



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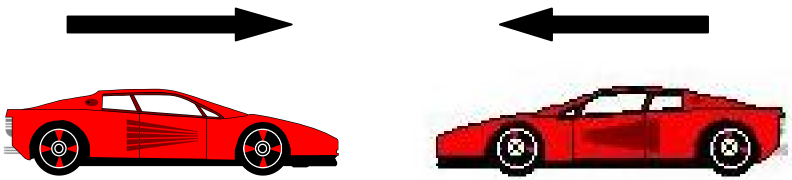
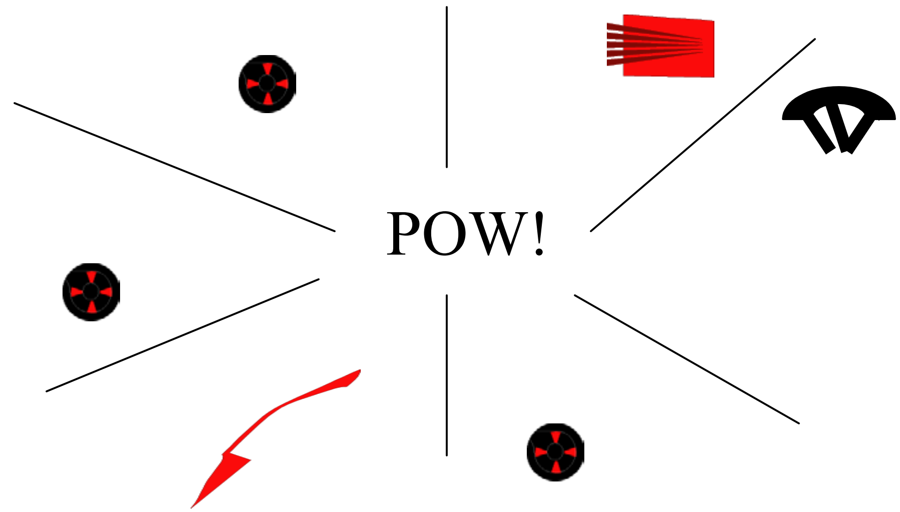
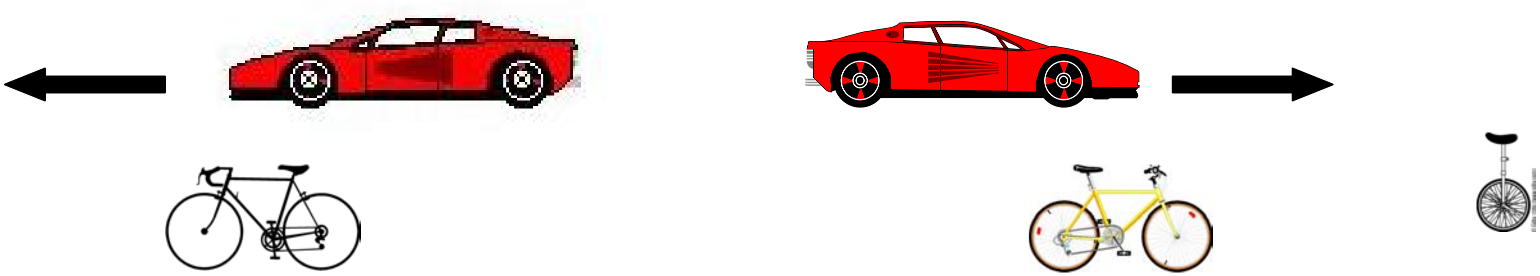




What are cars made of?

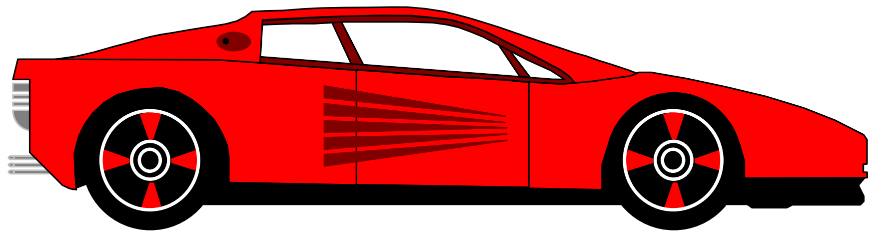
OK for nuclei
But for nucleons…



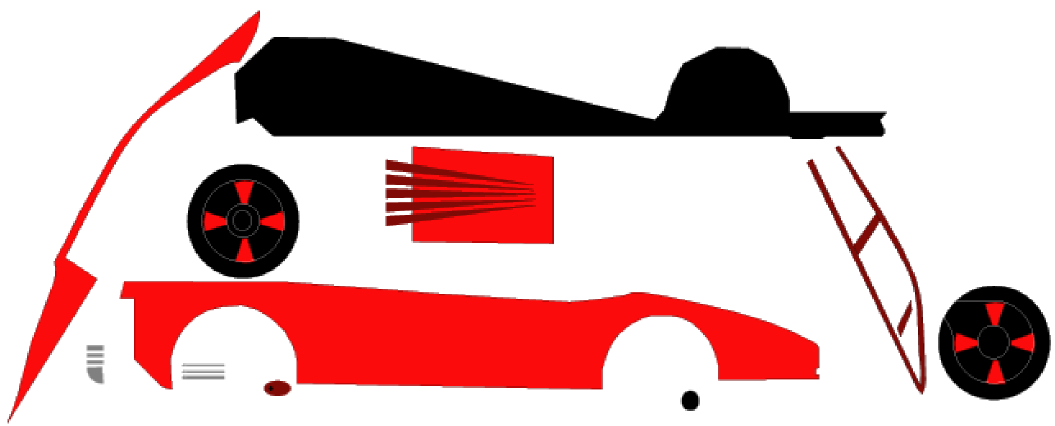
Why?

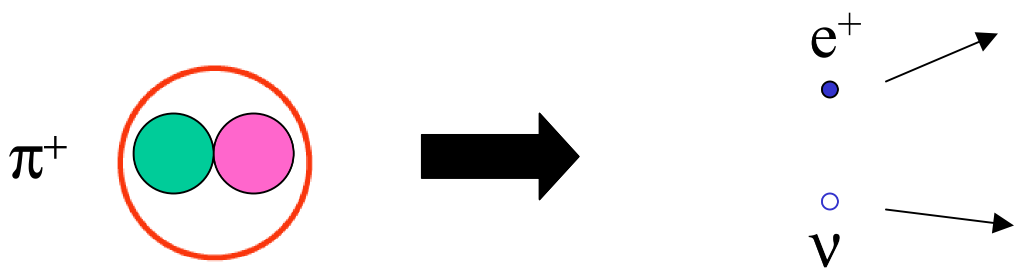
$E=mc^2$ and quarks

Passive



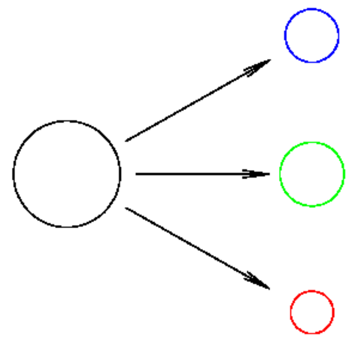
Wait a few years



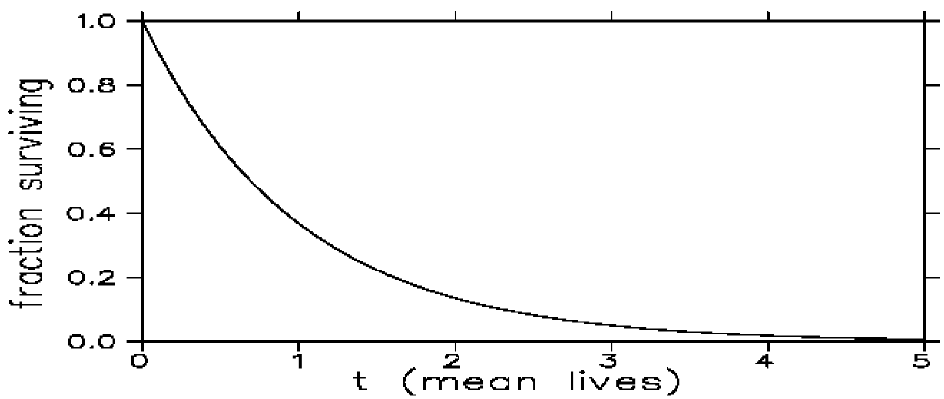


Particle Decay

All but a handful of elementary particles have finite lifetimes. They spontaneously fall apart into lighter particles:

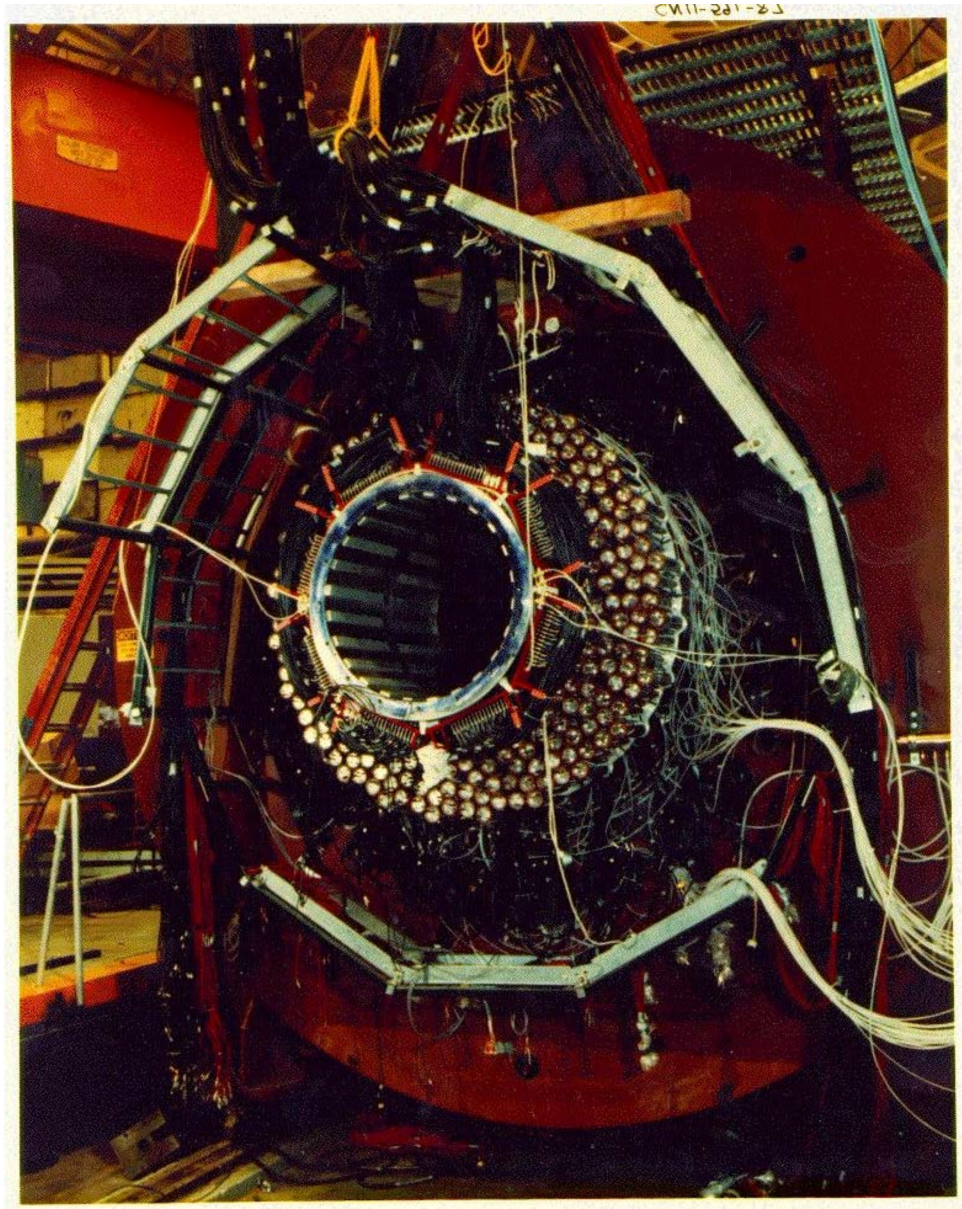


Unlike people, they have a constant probability of dying at any point in their lives:

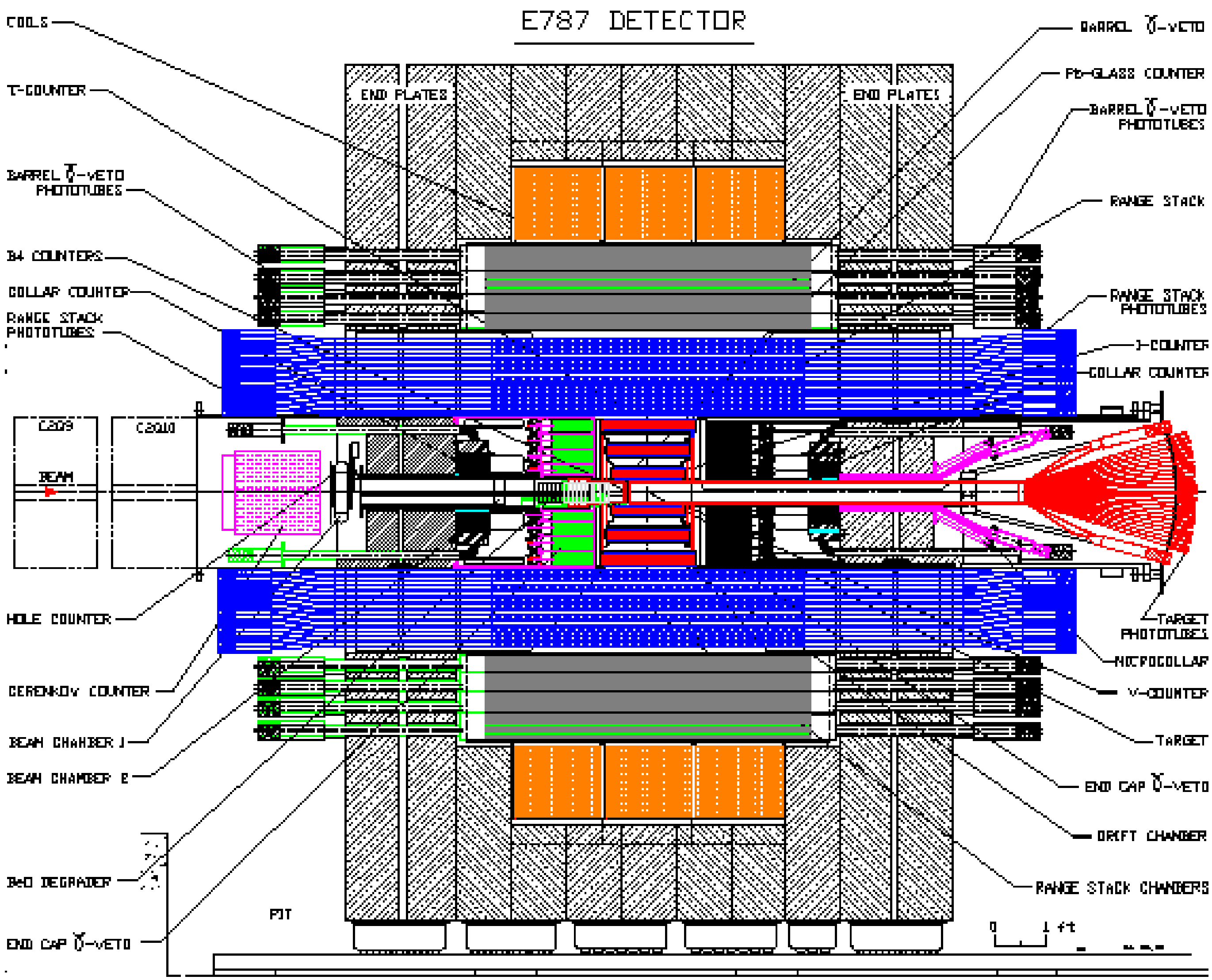


Most particles have several different decay schemes of "branches". Studying these is one of the main techniques of elementary particle experiment.

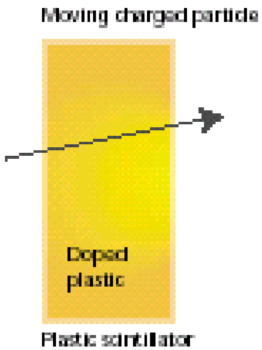
AGS Experiment (787)

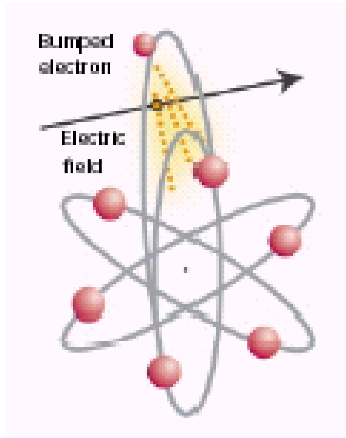


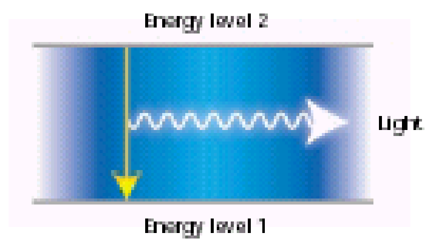
E787

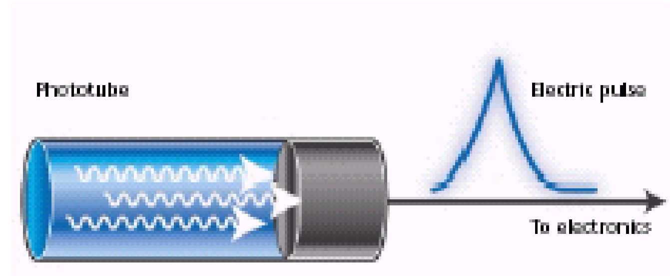

E787 DETECTOR
COILS
T-COUNTER
BARREL ℽ-VETO PHOTOTUBES
B4 COUNTERS
COLLAR COUNTER
RANGE STACK PHOTOTUBES
C209
C2010
BEAM
HOLE COUNTER
CERENKOV COUNTER
BEAM CHAMBER 1
BEAM CHAMBER 2
BeO DEGRADER
END CAP ℽ-VETO
PIT
END PLATES
END PLATES
BARREL ℽ-VETO
Pb-GLASS COUNTER
BARREL ℽ-VETO PHOTOTUBES
RANGE STACK
RANGE STACK PHOTOTUBES
I-COUNTER
COLLAR COUNTER
TARGET PHOTOTUBES
MICROCOLLAR
V-COUNTER
TARGET
END CAP ℽ-VETO
DRIFT CHAMBER
RANGE STACK CHAMBERS
0
1 ft

Scintillation Counter

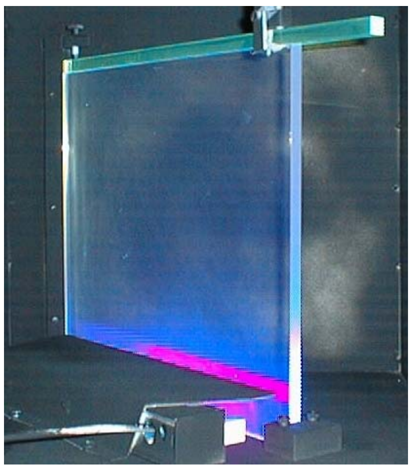


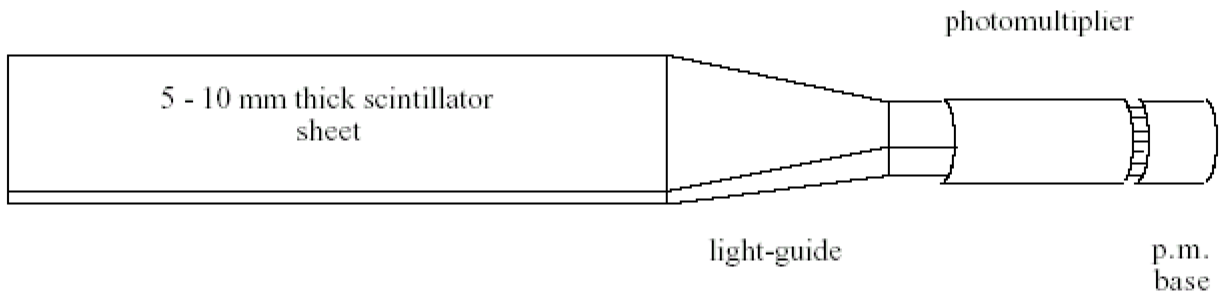


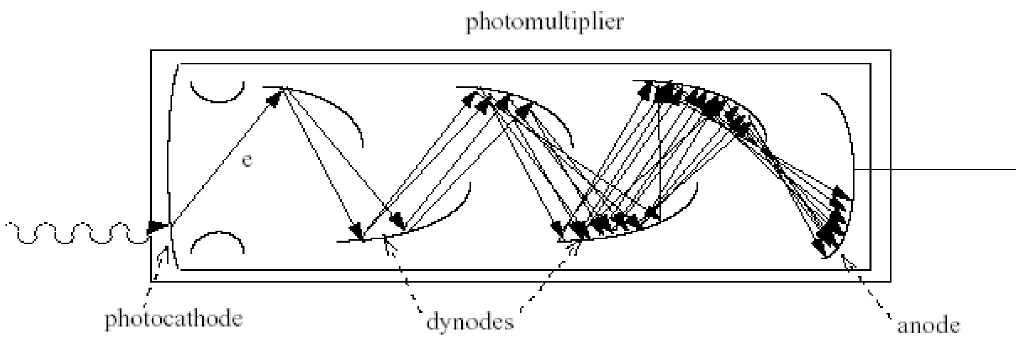




How a plastic scintillator works

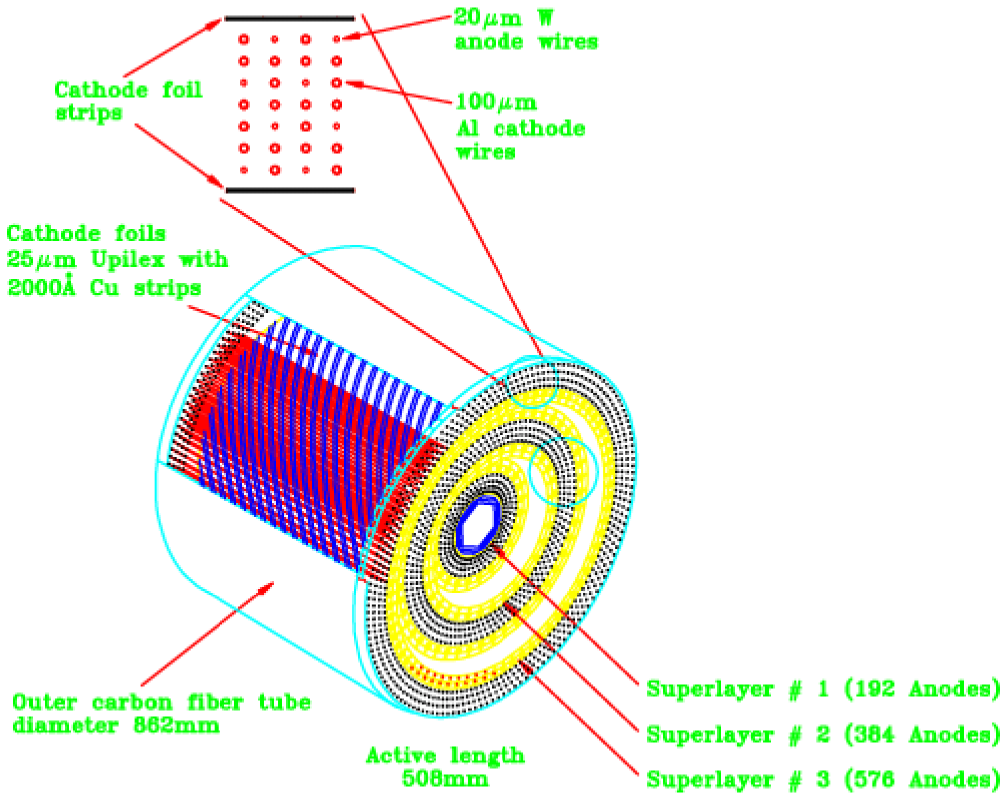


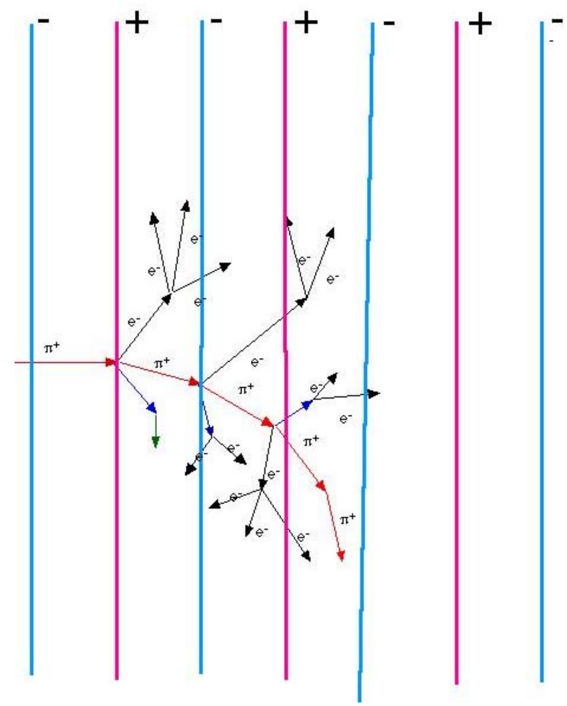


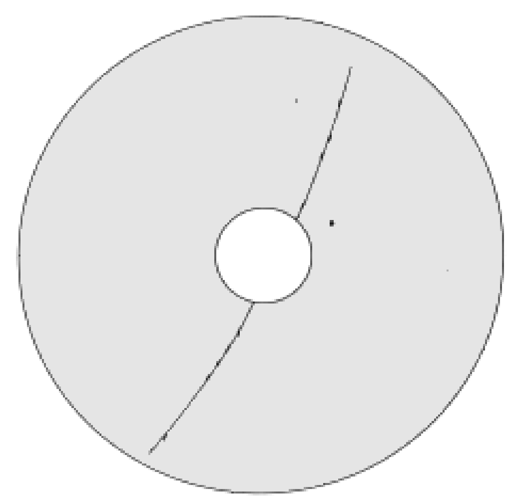


Drift Chamber

Charged particles ionize a gas on which a high electric field is imposed. Drift time of the ions in the field is used to locate the tracks of the particles

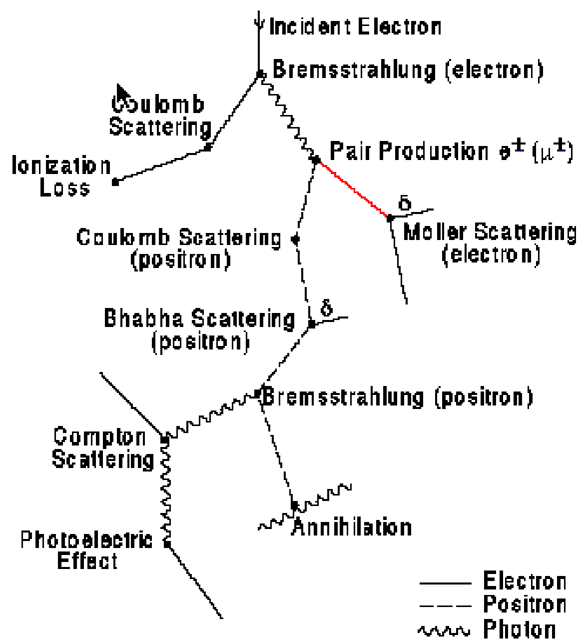


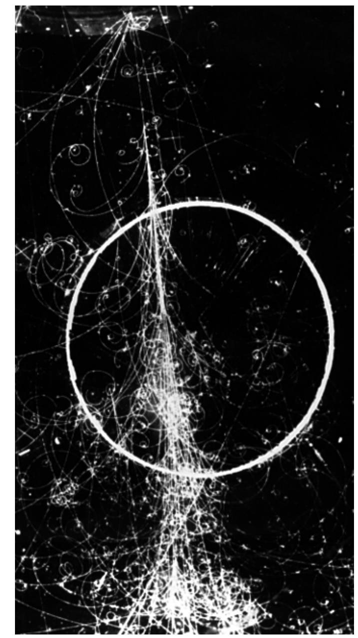




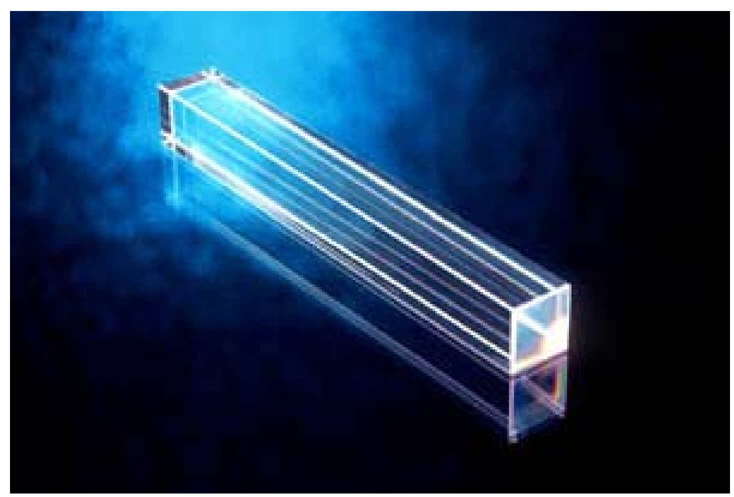
Electromagnetic Calorimeter

High energy photons (γ `s) convert to $e^+ e^-$ pairs in matter. The $e^+$ and $e^-$ radiate $\gamma$ `s which then convert to $e^+ e^-$ pairs and the process repeats until all the energy of the original γ has been lost. If the material is sensitive to the ionization energy the e^+ and e^- deposit, the γ energy can be measured. Incident e^+ or e^- also "shower" in such materials & their energies can be measured in the same way.



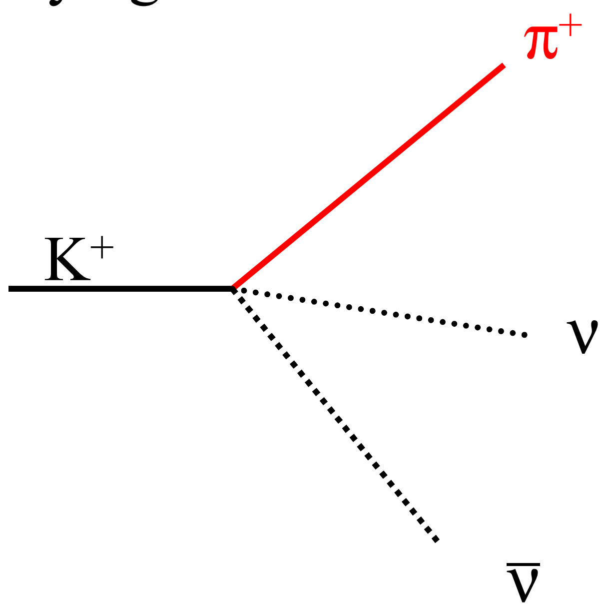


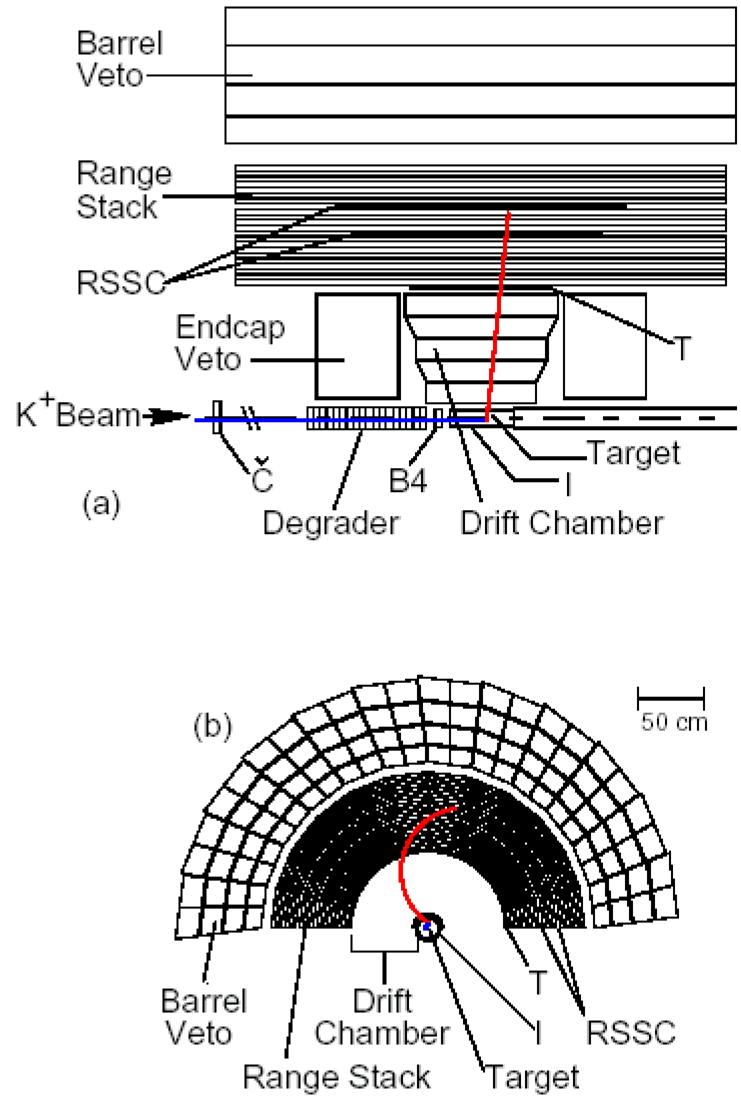
The probability for these processes are greatest in heavy materials (those with large atomic number) like lead, so that certain crystals that contain such materials and which also happen to scintillate are ideal for this purpose.



E787 Apparatus Simplified

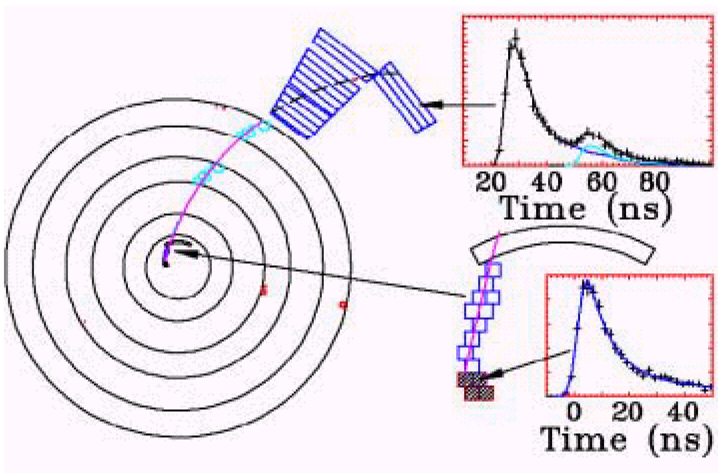
Trying to find:

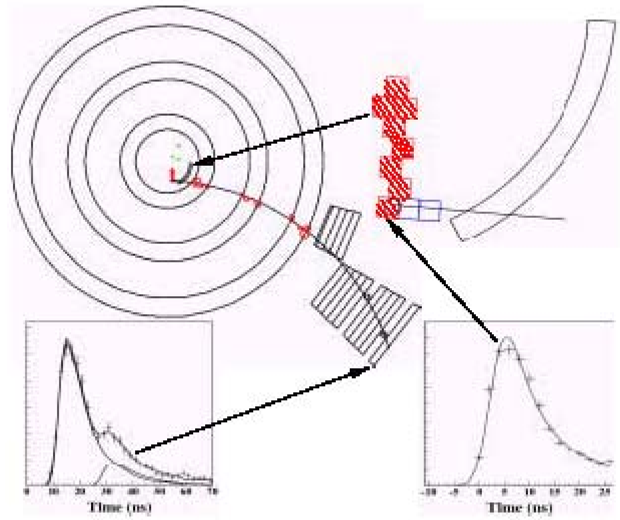




Happens 1 in 10 billion decays

E787 Events





Two events found, one expected, need much
more statistics to know what is going on
New experiment started, but future not clear

Capsule History

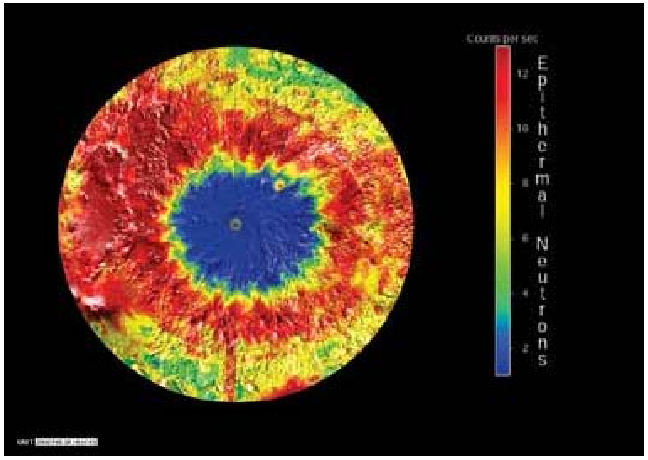
- 1920's, QM established, spin, e^- & proton known, e^+ predicted.
- 1930's, e^+, muon, neutron discovered, theory of nuclear force, ν predicted, Fermi theory of weak interactions, cyclotron invented
- 1940's, pions, kaons discovered, triumph of QED
- 1950's, ν's directly observed, antiproton discovered, many meson and baryons observed, resonances, "strangeness" hypothesis, neutral kaon system discovered, prediction & discovery of parity violation, V-A theory, bubble chamber invented
- 1960's, quark hypothesis, hints of "color", observation of CP-violation, separate "flavors" of ν's, theory of electroweak unification, solar neutrino problem, invention of colliding beam accelerators
- 1970's, QCD, beginning of string theory, discovery of charm and bottom quarks, τ lepton, gluon, Kobayashi-Maskawa explanation of CP-violation
- 1980's, discovery of intermediate vector bosons
- 1990's, discovery of the top quark, indications that ν's mix (& have mass).
- 2000's (so far), direct observation of the τ, confirmation that solar ν's mix, observation of CP-violation in the B-system

Some Open Issues

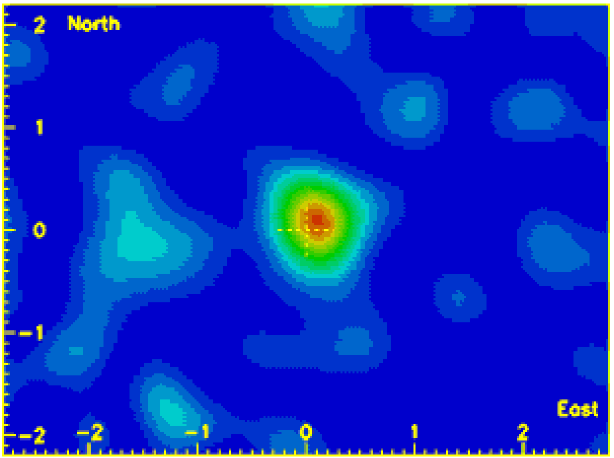
- Does a simple Standard Model Higgs particle exist?
  - If so, what is its mass? (We know it is > 114 GeV)
  - If not, what breaks electro-weak symmetry?
- What's the neutrino mass spectrum?
- What's the neutrino mixing matrix? (Do they violate CP?)
- Is charged lepton flavor conserved? (Does $\mu \rightarrow e\gamma$?)
- Is baryon number conserved? (Does the proton decay?)
- Is there sub-structure to quarks?
- Is the a unified theory of all four known forces?
- How many dimensions to we live in?
  - Does string theory have anything to do with reality?
  - Are there large extra dimensions?
- What is dark matter?
- What could possibly explain dark energy?

Some Applications of Particle Physics

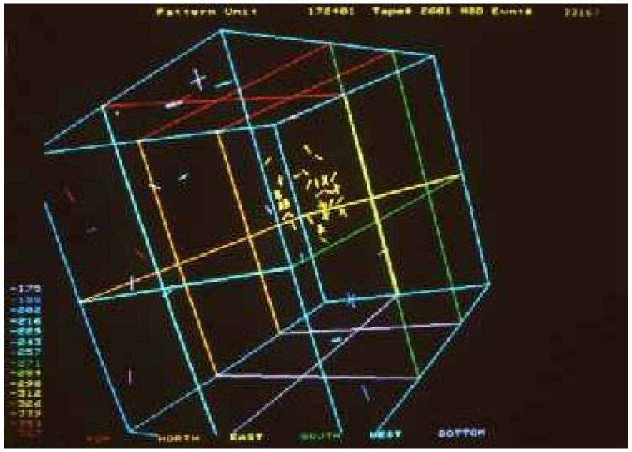
Synchrotron radiation from an electron beam, once an
annoyance, now a major tool for many branches of science



Neutrons from cosmic rays striking the planet Mars
Probe the distribution of hydrogen on the surface



Xray of the moon using cosmic ray muons
seen in the Soudan proton decay detector



Neutrino from SN1987A supernova seen in
Irvine-Michigan-Brookhaven proton decay detector